Neutrinos: Masses and challenges

Marilena LoVerde
C. N. Yang Institute for Theoretical Physics, Stony Brook University

Outline

- Neutrino mass
- Neutrino mass effects on cosmological observables
- Opportunities & challenges
- Conclusion/Discussion

Neutrino mass

Neutrino mass

Cosmology is sensitive to the energy density in cosmic neutrino background

$\rho_\nu \sim T_\nu^4$

early times, when relativistic

$\rho_\nu \sim \Sigma\, m_\nu\, n_\nu$

late times, when nonrelativistic

Neutrino mass

Cosmology is sensitive to the energy density in cosmic neutrino background

$\rho_\nu \sim T_\nu^4$

early times, when relativistic

✓ CMB detects this, consistent with 3 species with temp $T_\nu \approx 0.00017$ eV

$\Rightarrow n_\nu \approx 336/\mathrm{cm}^3$

$\rho_\nu \sim \Sigma\, m_\nu\, n_\nu$

late times, when nonrelativistic

Neutrino mass

Cosmology is sensitive to the energy density in cosmic neutrino background

$\rho_\nu \sim T_\nu^4$

early times, when relativistic

✓ CMB detects this, consistent with 3 species with temp $T_\nu \approx 0.00017$ eV

$\Rightarrow n_\nu \approx 336/\mathrm{cm}^3$

$\rho_\nu \sim \Sigma\, m_\nu\, n_\nu$

late times, when nonrelativistic

$\sum m_\nu < 0.29$eV (WiggleZ + WMAP+ H0, Reimer-Sorenson et al 2015)

$\sum m_\nu < 0.59$eV (CMB only, Planck 2015)

$\sum m_\nu < 0.17$eV (CMB +BAO, Planck 2015)

$\sum m_\nu = 0.36 \pm 0.14$eV (BOSS + Planck, Beutler et al 2014)

$\sum m_\nu < 1.1$eV (BOSS Lyman-α, Palanque-Delabrouille 2015)

$\sum m_\nu < 0.14$eV (BOSS Lyman-α + CMB+ BAO, Palanque-Delabrouille 2015)

. . .

Neutrino mass

Cosmology is sensitive to the energy density in cosmic neutrino background

$\rho_\nu \sim T_\nu^4$

early times, when relativistic

✓ CMB detects this,
consistent with 3 species
with temp $T_\nu \approx 0.00017$ eV

$\Rightarrow n_\nu \approx 336/\mathrm{cm}^3$

$\rho_\nu \sim \Sigma\, m_\nu n_\nu$

late times, when nonrelativistic

$\sum m_\nu < 0.29$eV (WiggleZ + WMAP+ H0, Reimer-Sorenson et al 2015)

$\sum m_\nu < 0.59$eV (CMB only, Planck 2015)

$\sum m_\nu < 0.17$eV (CMB +BAO, Planck 2015)

Future CMB + BAO and/or galaxy clustering forecasted to reach σ_{M_ν} around 0.016eV

$\sum m_\nu < 0.14$eV (BOSS Lyman-α + CMB+ BAO, Palanque-Delabrouille 2015)

. . .

Neutrino mass

Oscillation data gives a lower bound

$$\Delta m_{12}^2 = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ \mathrm{eV}$$

$$|\Delta m_{13}^2| \simeq 2.4 \pm 0.06 \quad \times 10^{-3}\ \mathrm{eV}$$

Minimum mass for Normal Hierarchy $\sum m_{\nu i} \gtrsim 0.058\mathrm{eV}$

Minimum mass for Inverted Hierarchy $\sum m_{\nu i} \gtrsim 0.098\mathrm{eV}$

Neutrino mass

Oscillation data gives a lower bound

$$\Delta m_{12}^2 = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ \mathrm{eV}$$

$$|\Delta m_{13}^2| \simeq 2.4 \pm 0.06 \quad \times 10^{-3}\ \mathrm{eV}$$

Minimum mass for Normal Hierarchy $\sum m_{\nu i} \gtrsim 0.058\mathrm{eV}$

Minimum mass for Inverted Hierarchy $\sum m_{\nu i} \gtrsim 0.098\mathrm{eV}$

Future CMB + BAO and/or galaxy clustering forecasted to reach $\sigma_{M\nu}$ around 0.016eV

Neutrino mass

Oscillation data gives a lower bound

$$\Delta m_{12}^2 = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ \mathrm{eV}$$

$$|\Delta m_{13}^2| \simeq 2.4 \pm 0.06 \quad \times 10^{-3}\ \mathrm{eV}$$

Minimum mass for Normal Hierarchy $\sum m_{\nu i} \gtrsim 0.058\mathrm{eV}$

Minimum mass for Inverted Hierarchy $\sum m_{\nu i} \gtrsim 0.098\mathrm{eV}$

Cosmology can detect the neutrino mass scale

Cosmology can rule out Inverted Hierarchy

Information about the neutrino mass splitting is in cosmological data, but it seems to out of reach to detect

Neutrino mass effects on cosmological observables

The existence of neutrino mass changes ρ_ν (a), and therefore $H(a)$, $D_A(a)$

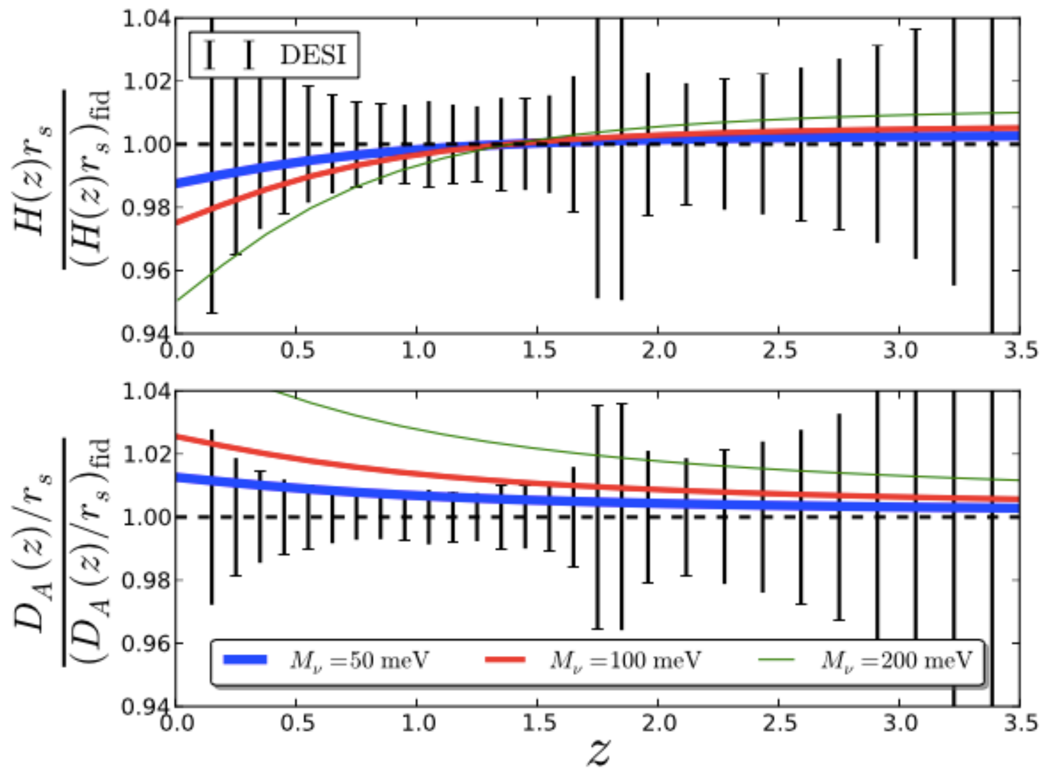


Figure 1. The dependence of expansion rate $H(z)$ and comoving angular diameter distance $D_A(z)$ on M_ν, where we minimize the $\chi^2(\Theta, M_\nu)$ by adjust the 6 ΛCDM parameters Θ when increasing M_ν from 0 to $50, 100, 200$ meV.

Pan & Knox 2014

And changes the evolution of density perturbations:

And changes the evolution of density perturbations:

At fixed Ω_m, increasing the mass of neutrinos, M_ν, decreases the amount of clustering matter below $k_{\text{free-streaming}} \sim aHm_\nu/T_\nu$

And changes the evolution of density perturbations:

At fixed Ω_m, increasing the mass of neutrinos, M_ν, decreases the amount of clustering matter below $k_{\text{free-streaming}} \sim aHm_\nu/T_\nu$

Suppression in cold dark matter density fluctuations

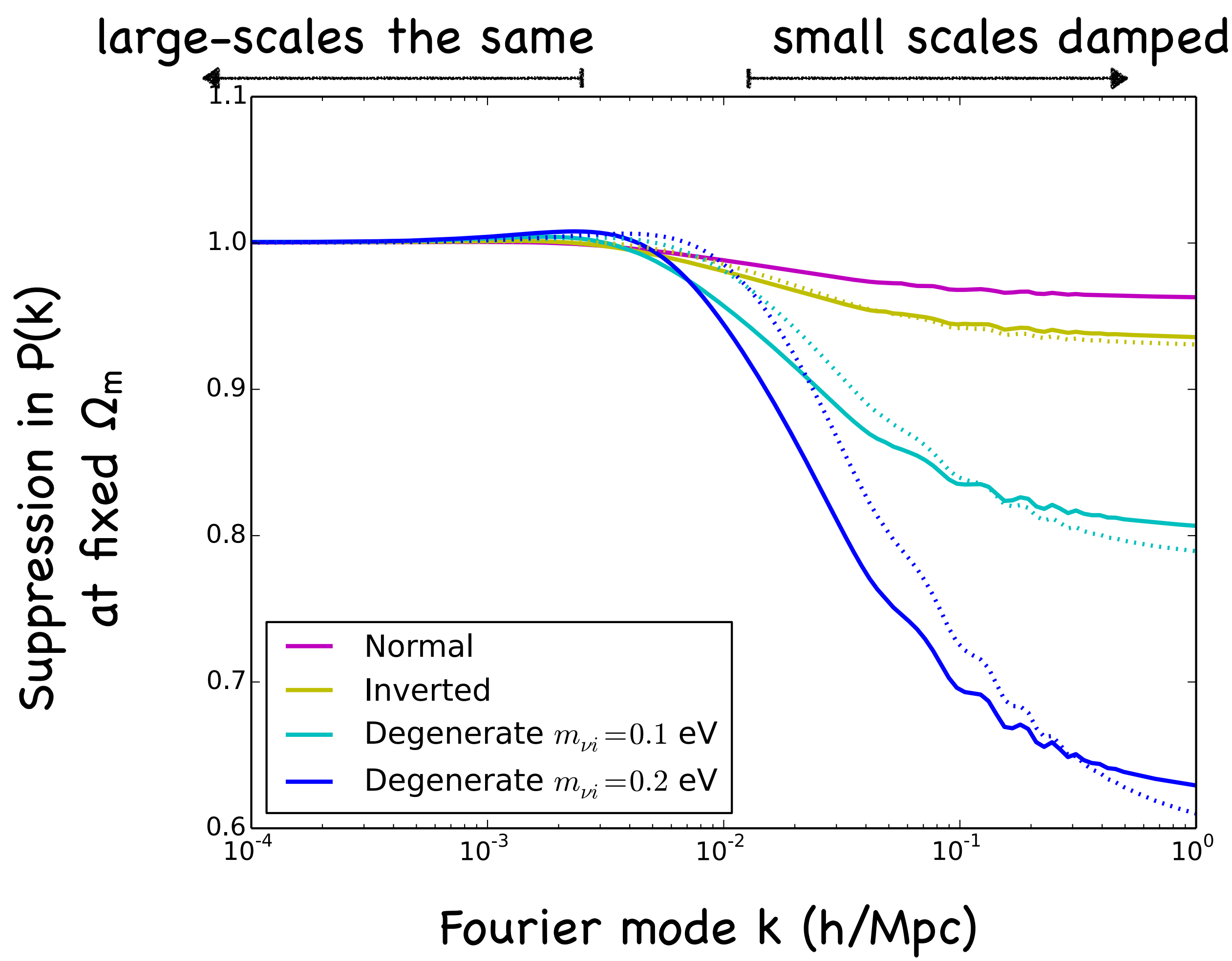
$$\frac{\delta_{cdm}(M_\nu)}{\delta_{cdm}(M_\nu = 0)} \sim \left(\begin{array}{c}\text{usual growth from} \\ \text{time neutrinos went} \\ \text{non-relativistic}\end{array}\right)^{-3/5\Omega_\nu/\Omega_m}$$

And changes the evolution of density perturbations:

At fixed Ω_m, increasing the mass of neutrinos, M_ν, decreases the amount of clustering matter below $k_{\text{free-streaming}} \sim aHm_\nu/T_\nu$

Suppression in cold dark matter density fluctuations

$$\frac{\delta_{cdm}(M_\nu)}{\delta_{cdm}(M_\nu = 0)} \sim \left(\begin{array}{c} \text{usual growth from} \\ \text{time neutrinos went} \\ \text{non-relativistic} \end{array} \right)^{-3/5\Omega_\nu/\Omega_m}$$

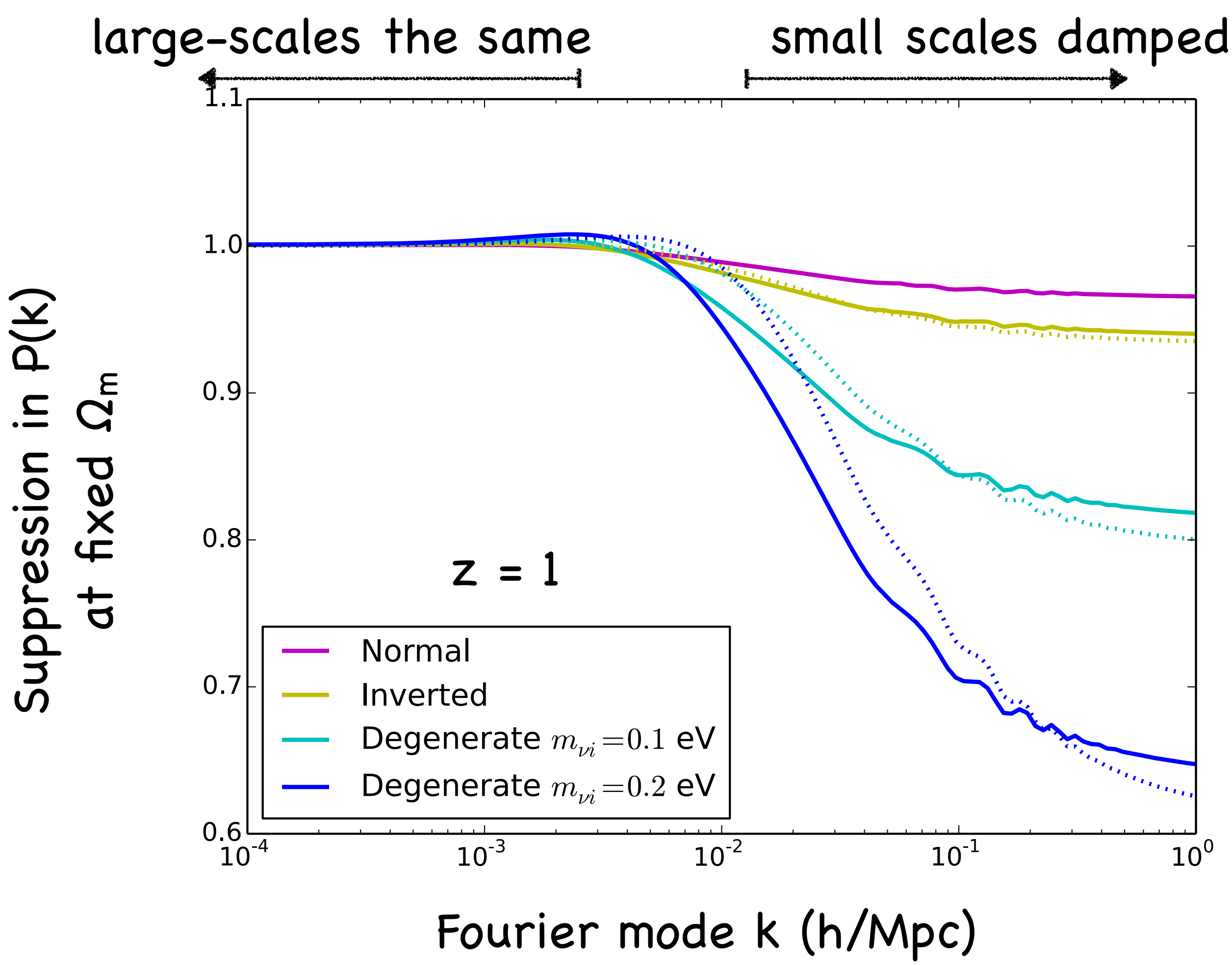


And changes the evolution of density perturbations:

At fixed Ω_m, increasing the mass of neutrinos, M_ν, decreases the amount of clustering matter below $k_{\text{free-streaming}} \sim aHm_\nu/T_\nu$

Suppression in cold dark matter density fluctuations

$$\frac{\delta_{cdm}(M_\nu)}{\delta_{cdm}(M_\nu = 0)} \sim \left(\begin{array}{c}\text{usual growth from} \\ \text{time neutrinos went} \\ \text{non-relativistic}\end{array} \right)^{-3/5\Omega_\nu/\Omega_m}$$

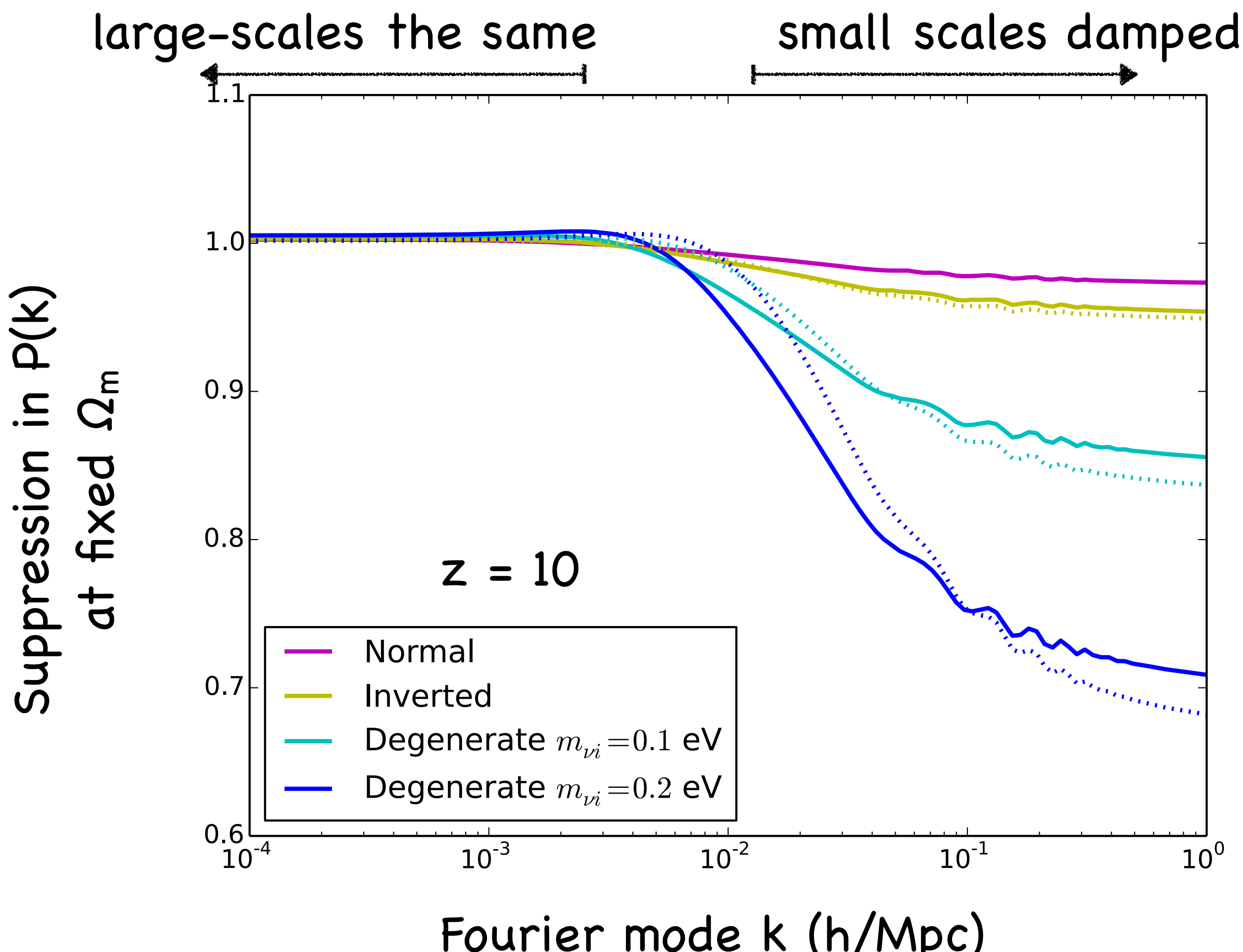


And changes the evolution of density perturbations:

At fixed Ω_m, increasing the mass of neutrinos, M_ν, decreases the amount of clustering matter below $k_{\text{free-streaming}} \sim aHm_\nu/T_\nu$

Suppression in cold dark matter density fluctuations

$$\frac{\delta_{cdm}(M_\nu)}{\delta_{cdm}(M_\nu = 0)} \sim \left(\begin{array}{c} \text{usual growth from} \\ \text{time neutrinos went} \\ \text{non-relativistic} \end{array} \right)^{-3/5\Omega_\nu/\Omega_m}$$



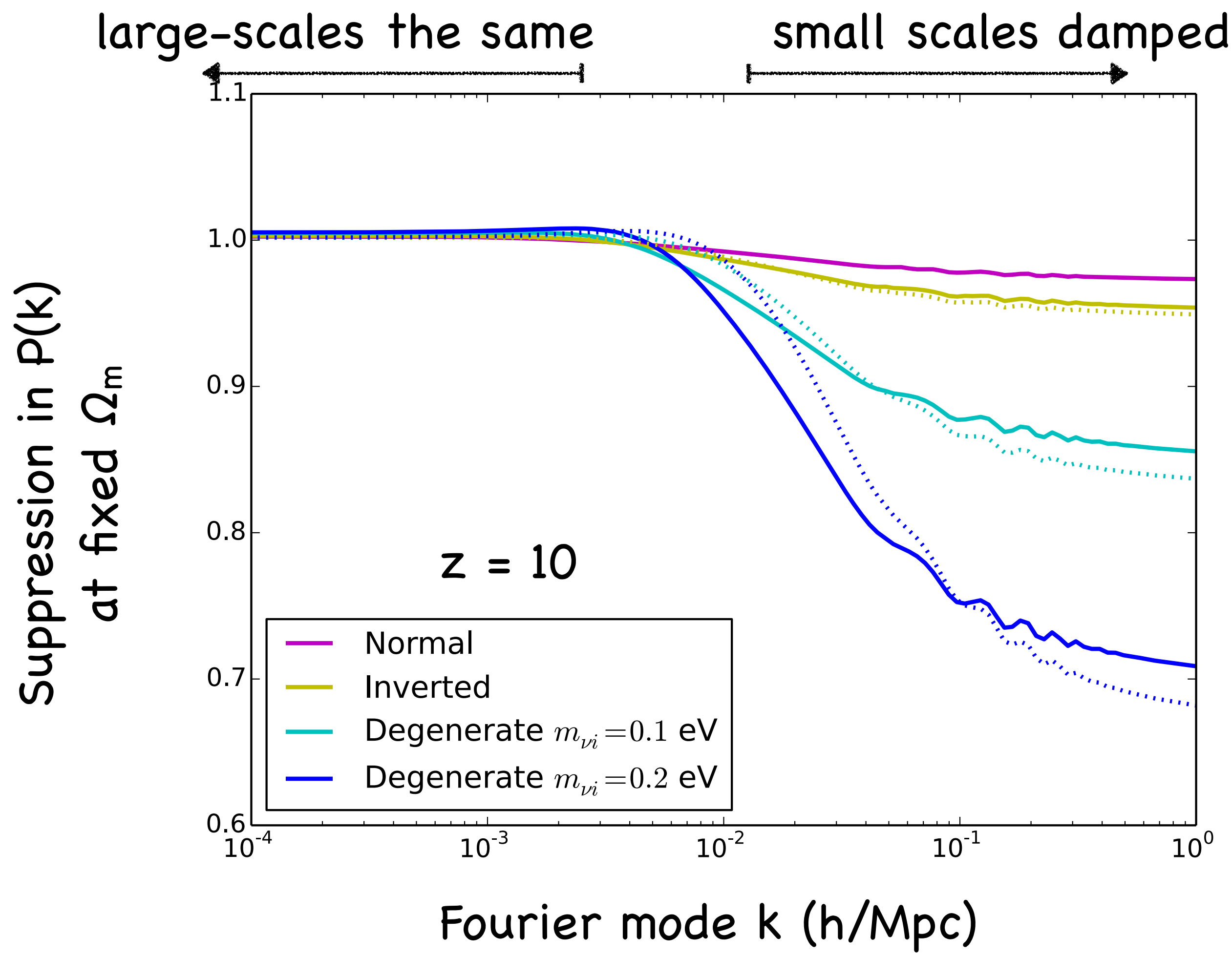
And changes the evolution of density perturbations:

At fixed Ω_m, increasing the mass of neutrinos, M_ν, decreases the amount of clustering matter below $k_{\text{free-streaming}} \sim aHm_\nu/T_\nu$

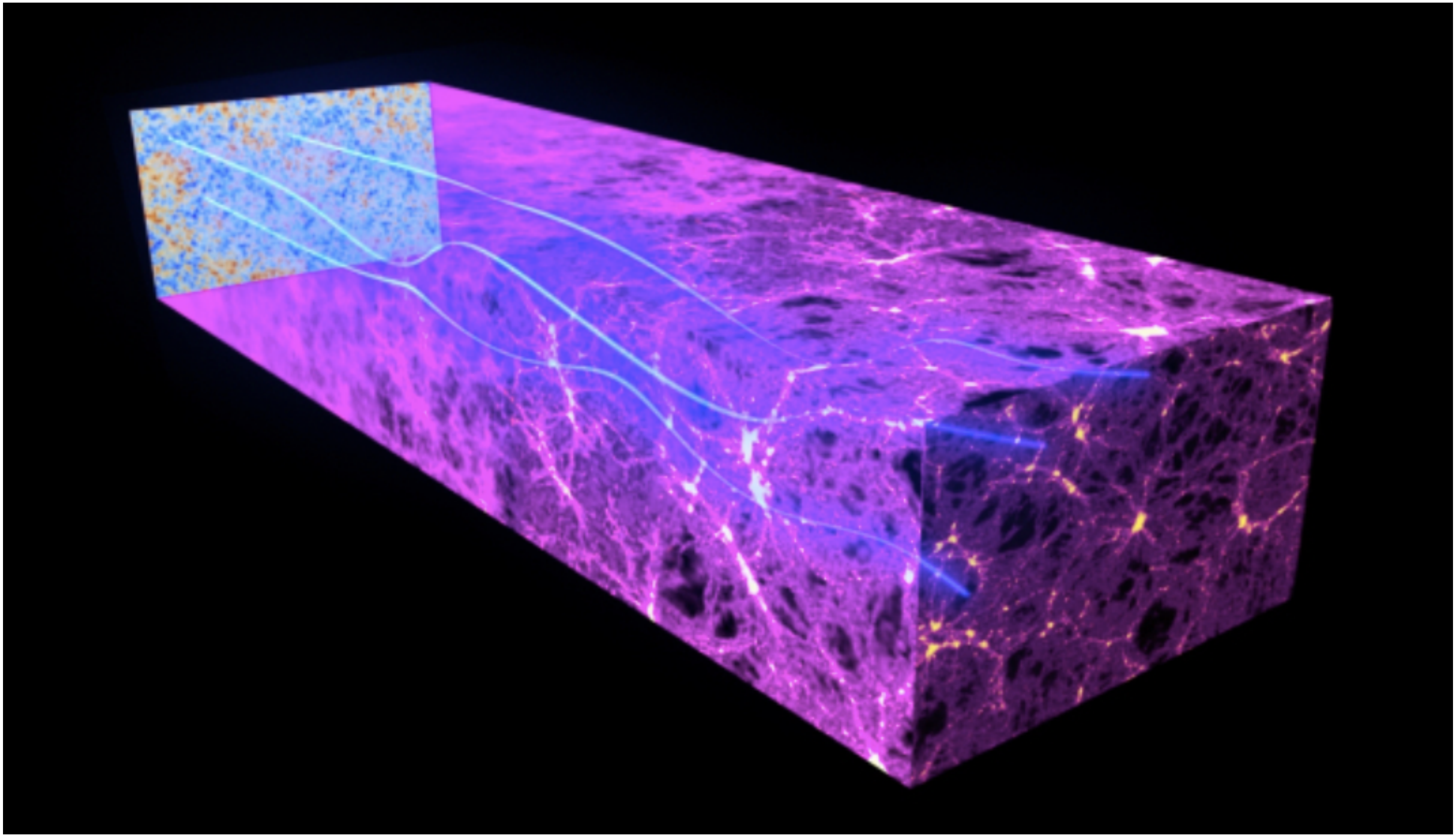
Suppression in cold dark matter density fluctuations

$$\frac{\delta_{cdm}(M_\nu)}{\delta_{cdm}(M_\nu = 0)} \sim \left(\begin{array}{c} \text{usual growth from} \\ \text{time neutrinos went} \\ \text{non-relativistic} \end{array} \right)^{-3/5\Omega_\nu/\Omega_m}$$

Suppression from neutrinos depends on time



Observables: Gravitational Lensing of CMB



(image from Planck)

Observables: Gravitational Lensing of CMB

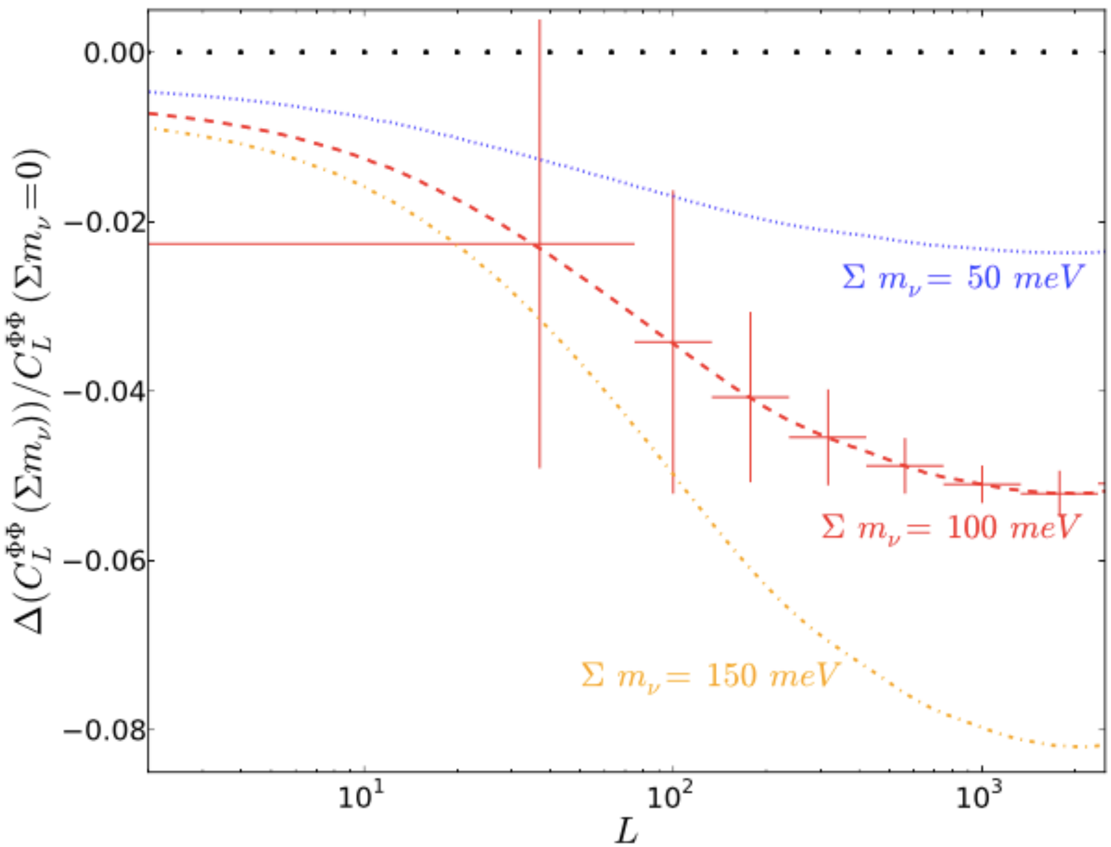


Figure 5. *The effect of massive neutrinos on the CMB lensing potential power spectrum fractional change in $C_L^{\Phi\Phi}$ for a given value of $\sum m_\nu$ is shown relative to the case for zero ne Projected constraints on $C_L^{\Phi\Phi}$ for a Stage-IV CMB experiment are shown for $\sum m_\nu = 100$ me have approximated all of the neutrino mass to be in one mass eigenstate and fixed the total m $\Omega_m h^2$ and H_0. The 1σ constraint for $\sum m_\nu$ is approximately 45 meV for lensing alone and drop when combined with other probes.*

Abazajian et al 2013

Observables: Gravitational Lensing of CMB

sensitive to:

- change in integrated amplitude of matter fluctuations between us and the CMB

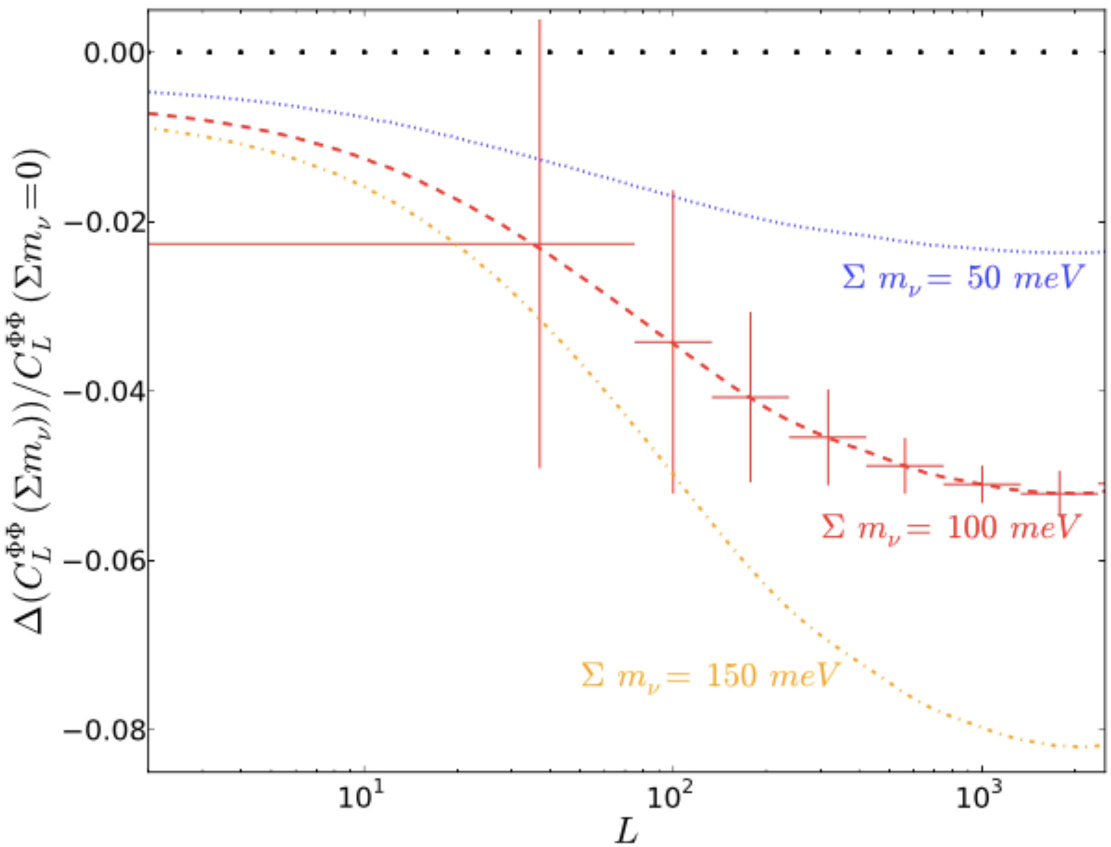


Figure 5. *The effect of massive neutrinos on the CMB lensing potential power spectrum fractional change in $C_L^{\Phi\Phi}$ for a given value of $\sum m_\nu$ is shown relative to the case for zero ne Projected constraints on $C_L^{\Phi\Phi}$ for a Stage-IV CMB experiment are shown for $\sum m_\nu = 100$ me have approximated all of the neutrino mass to be in one mass eigenstate and fixed the total ma $\Omega_m h^2$ and H_0. The 1σ constraint for $\sum m_\nu$ is approximately 45 meV for lensing alone and drop when combined with other probes.*

Abazajian et al 2013

Observables: Gravitational Lensing of CMB

sensitive to:

- change in integrated amplitude of matter fluctuations between us and the CMB

degeneracies:

- $\Omega_m h^2$ (total matter density)
- A_s (amplitude of primordial fluctuations)
- (and A_s is degenerate with τ, optical depth)
- dark energy

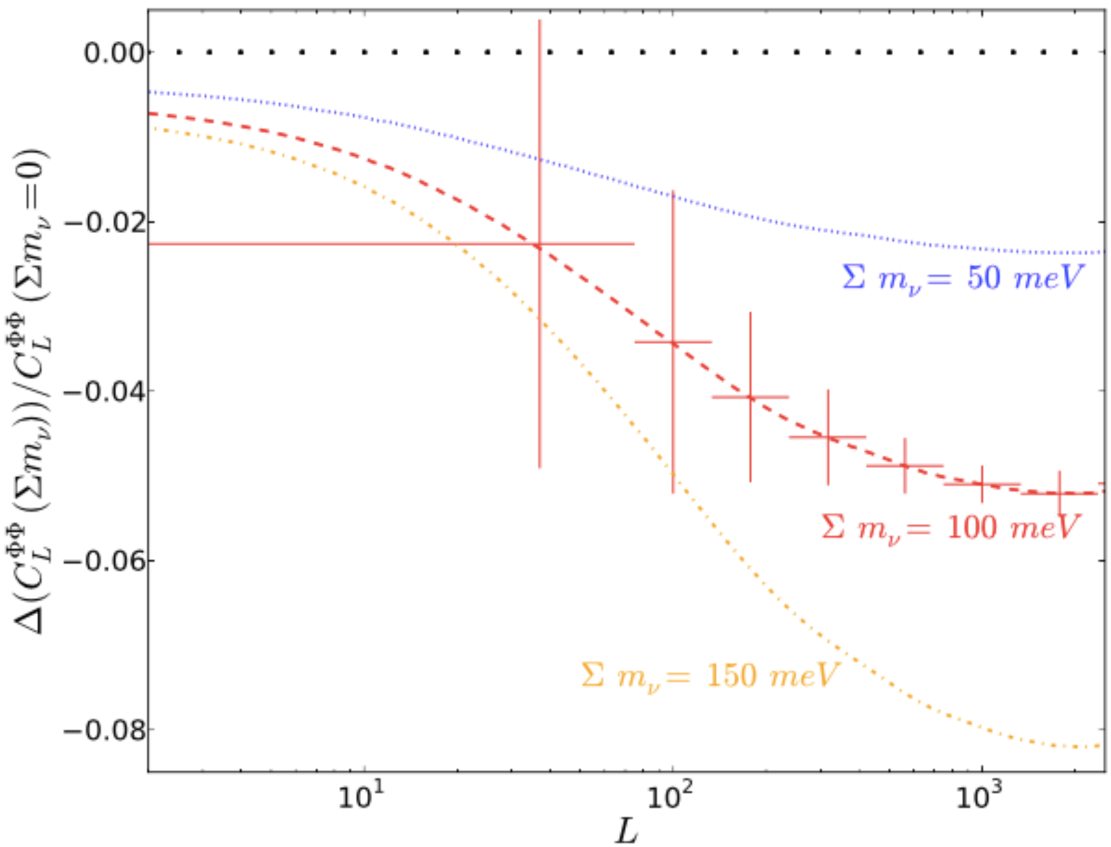


Figure 5. *The effect of massive neutrinos on the CMB lensing potential power spectrun fractional change in $C_L^{\Phi\Phi}$ for a given value of $\sum m_\nu$ is shown relative to the case for zero ne Projected constraints on $C_L^{\Phi\Phi}$ for a Stage-IV CMB experiment are shown for $\sum m_\nu = 100$ me have approximated all of the neutrino mass to be in one mass eigenstate and fixed the total ma $\Omega_m h^2$ and H_0. The 1σ constraint for $\sum m_\nu$ is approximately 45 meV for lensing alone and drop when combined with other probes.*

Abazajian et al 2013

Observables: Gravitational Lensing of CMB

sensitive to:

- change in integrated amplitude of matter fluctuations between us and the CMB

degeneracies:

- $\Omega_m h^2$ (total matter density)
- A_s (amplitude of primordial fluctuations)
- (and A_s is degenerate with τ, optical depth)
- dark energy

systematics:

- Polarized foregrounds that bias $C^{\Phi\Phi}_L$?
- modeling P(k) at 3% level?
- ?

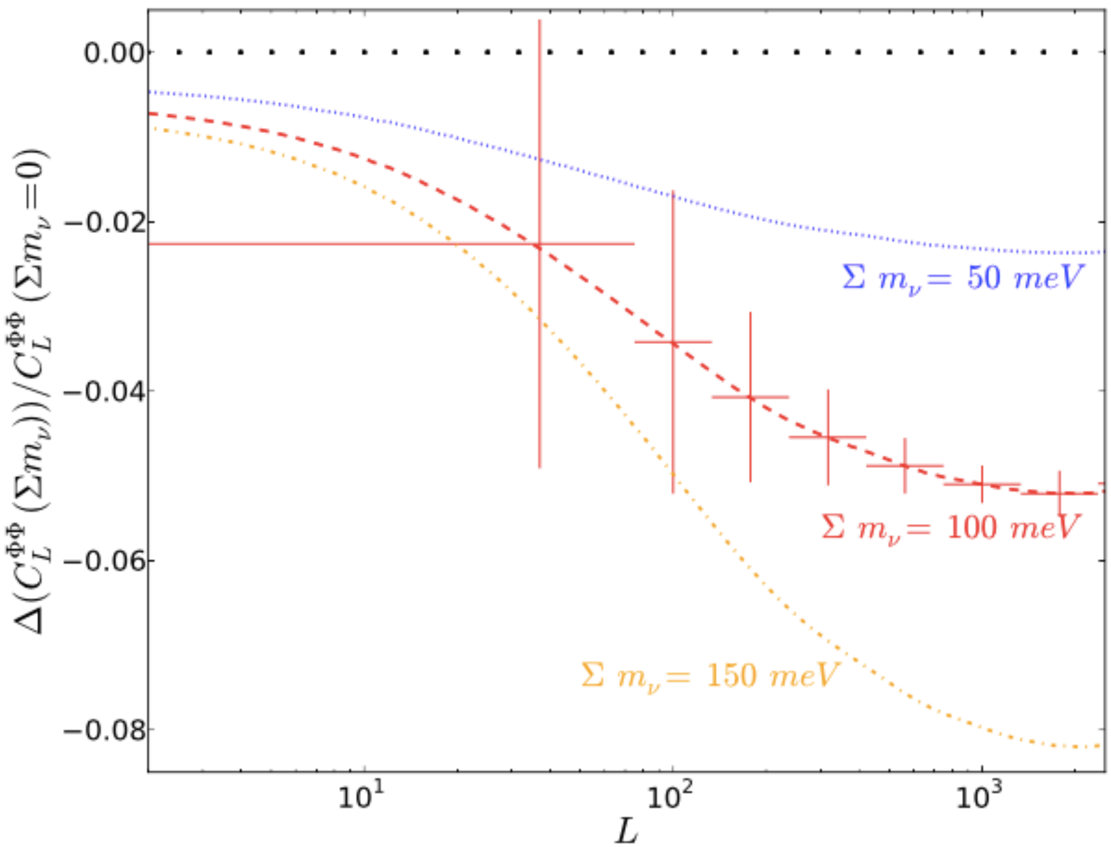


Figure 5. *The effect of massive neutrinos on the CMB lensing potential power spectrun fractional change in $C_L^{\Phi\Phi}$ for a given value of $\sum m_\nu$ is shown relative to the case for zero ne Projected constraints on $C_L^{\Phi\Phi}$ for a Stage-IV CMB experiment are shown for $\sum m_\nu = 100$ me have approximated all of the neutrino mass to be in one mass eigenstate and fixed the total ma $\Omega_m h^2$ and H_0. The 1σ constraint for $\sum m_\nu$ is approximately 45 meV for lensing alone and drop when combined with other probes.*

Abazajian et al 2013

Observables: Gravitational Lensing of CMB

sensitive to:

- change in integrated amplitude of matter fluctuations between us and the CMB

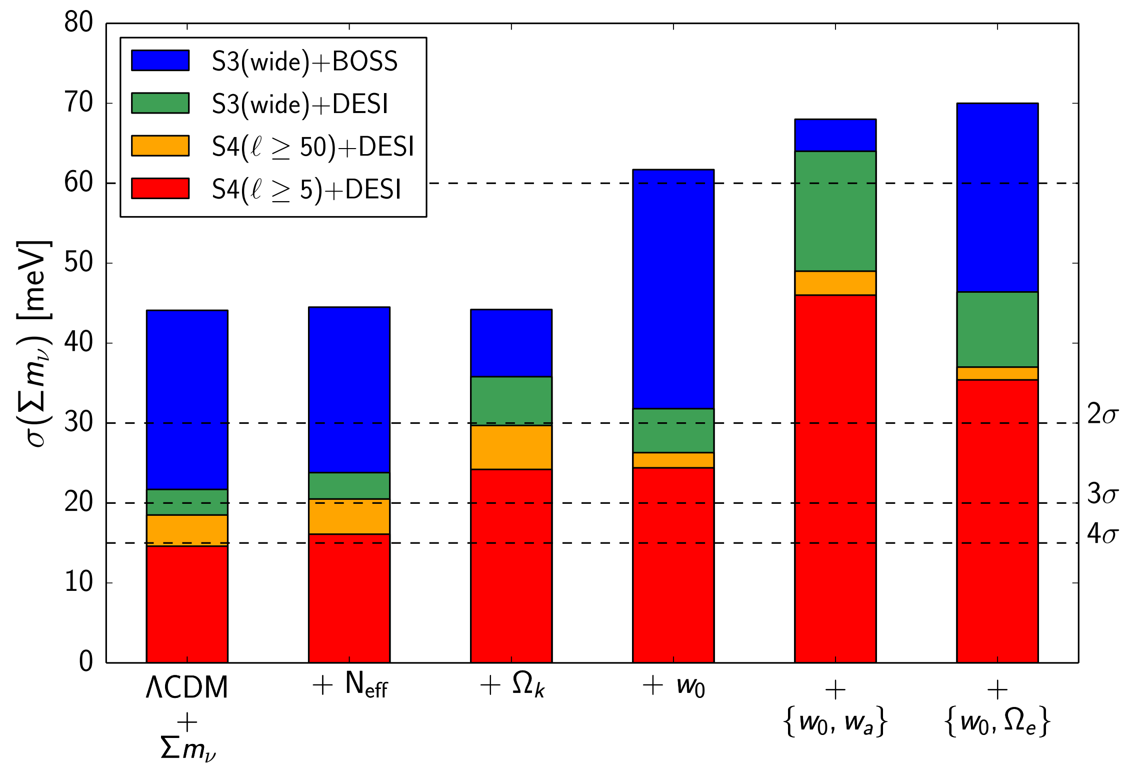
degeneracies:

- $\Omega_m h^2$ (total matter density)
- A_s (amplitude of primordial fluctuations)
- (and A_s is degenerate with τ, optical depth)
- dark energy

systematics:

- Polarized foregrounds that bias $C^{\Phi\Phi}_L$?
- modeling P(k) at 3% level?
- ?

CMB Lensing + BAO 3-4σ → detection of 0.058eV



Allison et al 2015

Observables: Gravitational Lensing of CMB

sensitive to:

- change in integrated amplitude of matter fluctuations between us and the CMB

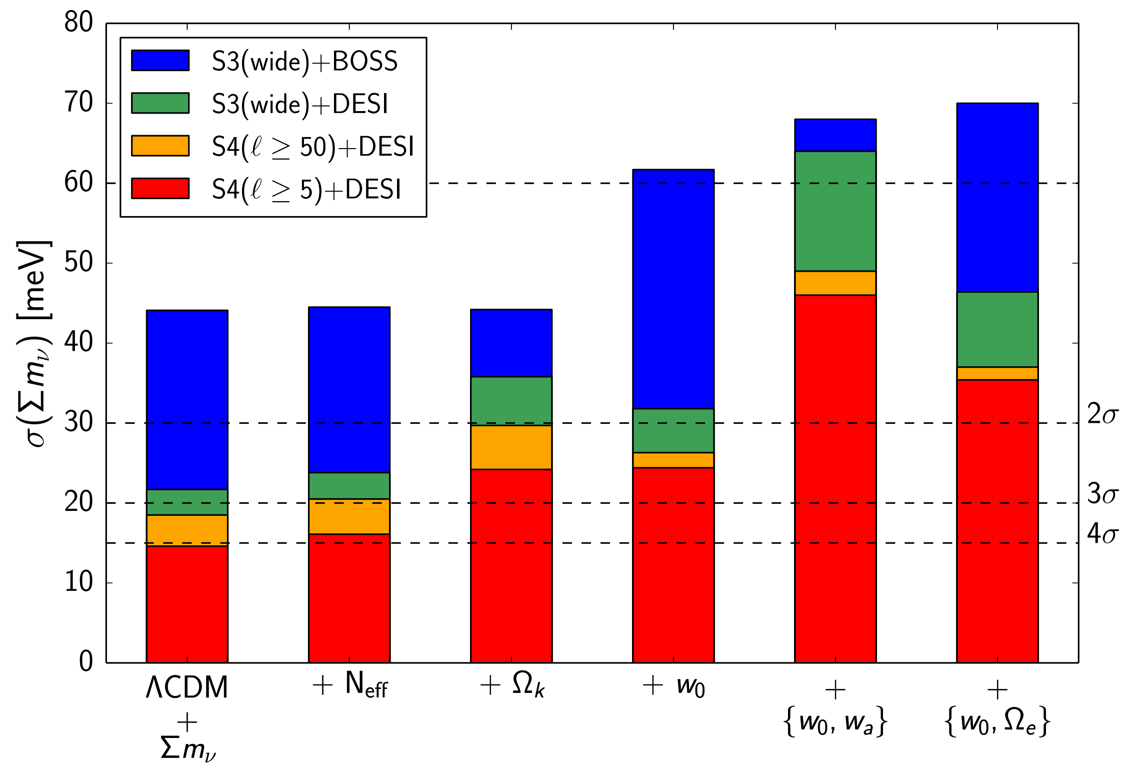
degeneracies:

- $\Omega_m h^2$ (total matter density)
- A_s (amplitude of primordial fluctuations)
- (and A_s is degenerate with τ, optical depth)
- dark energy

systematics:

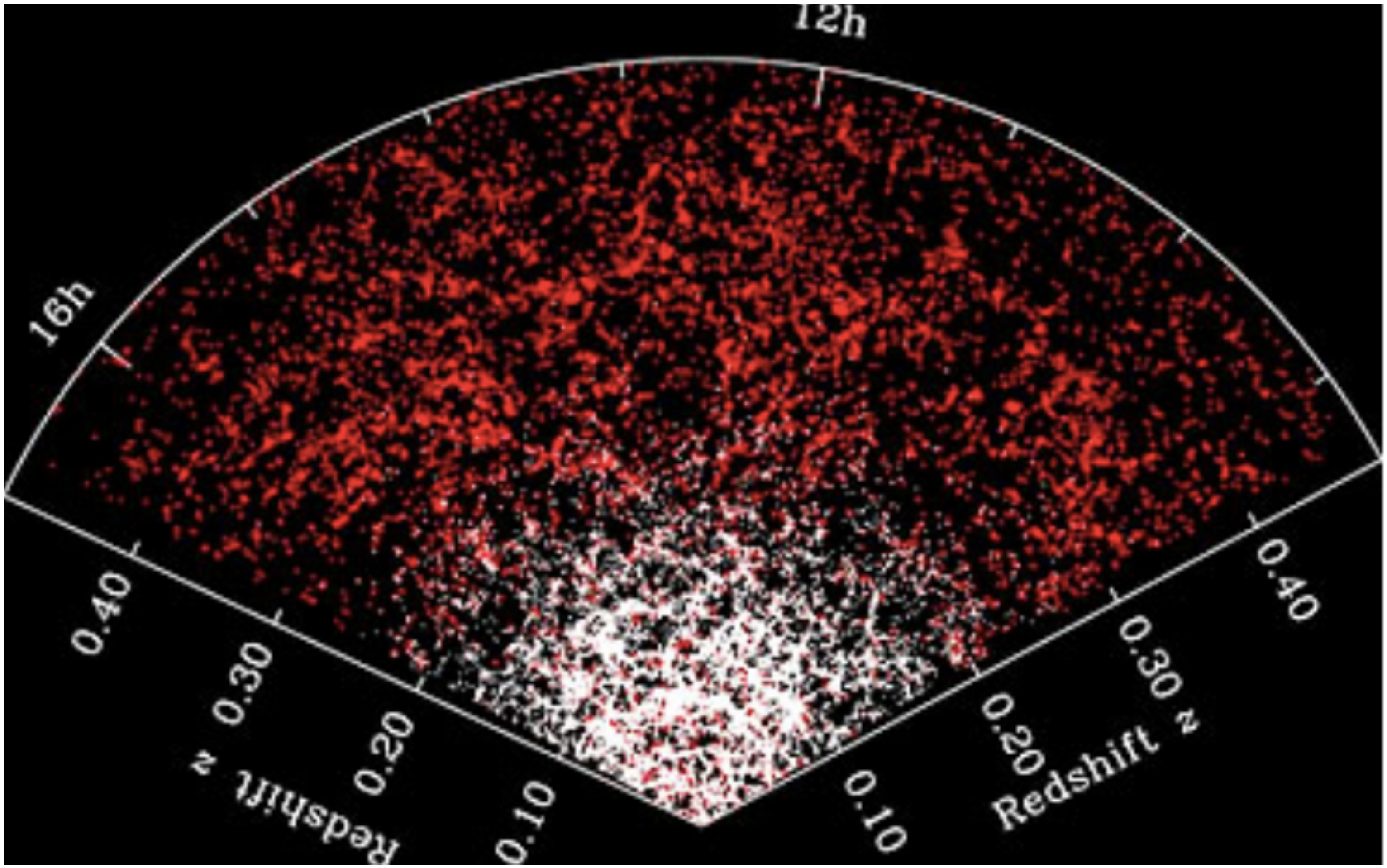
- Polarized foregrounds that bias $C^{\Phi\Phi}_L$?
- modeling P(k) at 3% level?
- ?

CMB Lensing **+ BAO** 3-4σ → detection of 0.058eV



Allison et al 2015

Observables: Spectroscopic Galaxy Clustering



Sloan Digital Sky Survey

Observables: Spectroscopic Galaxy Clustering

sensitive to:

- change in amplitude of galaxy fluctuations at redshift(s) of measurement z
- change of rate of change of growth of matter fluctuations at z

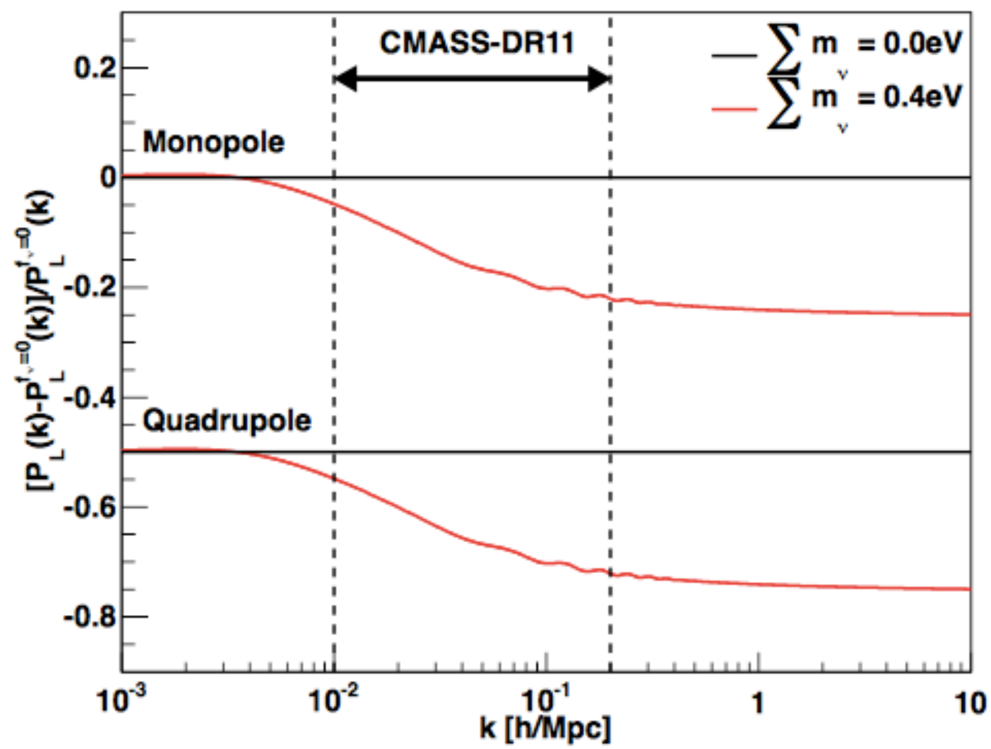


Figure 2. Relative amplitude difference between a linear power spectrum monopole (top) and quadrupole (bottom) with $\sum m_\nu = 0\,\mathrm{eV}$ (black lines) and $\sum m_\nu = 0.4\,\mathrm{eV}$ (red lines). We keep $\Omega_c h^2$ fixed when including the neutrino mass, so that the total physical matter density increases as $\Omega_m h^2 = \Omega_c h^2 + \Omega_b h^2 + \Omega_\nu h^2$. The black dashed lines show the fitting range for the CMASS-DR11 results of Beutler et al. (2013). We subtract 0.5 from the quadrupole for plotting purposes.

Beutler et al 2014

Observables: Spectroscopic Galaxy Clustering

sensitive to:

- change in amplitude of galaxy fluctuations at redshift(s) of measurement z
- change of rate of change of growth of matter fluctuations at z

degeneracies:

- dark energy/modified gravity
- astrophysics? galaxy bias?
- $\Omega_m h^2$ (total matter density)
- A_s (amplitude of primordial fluctuations)

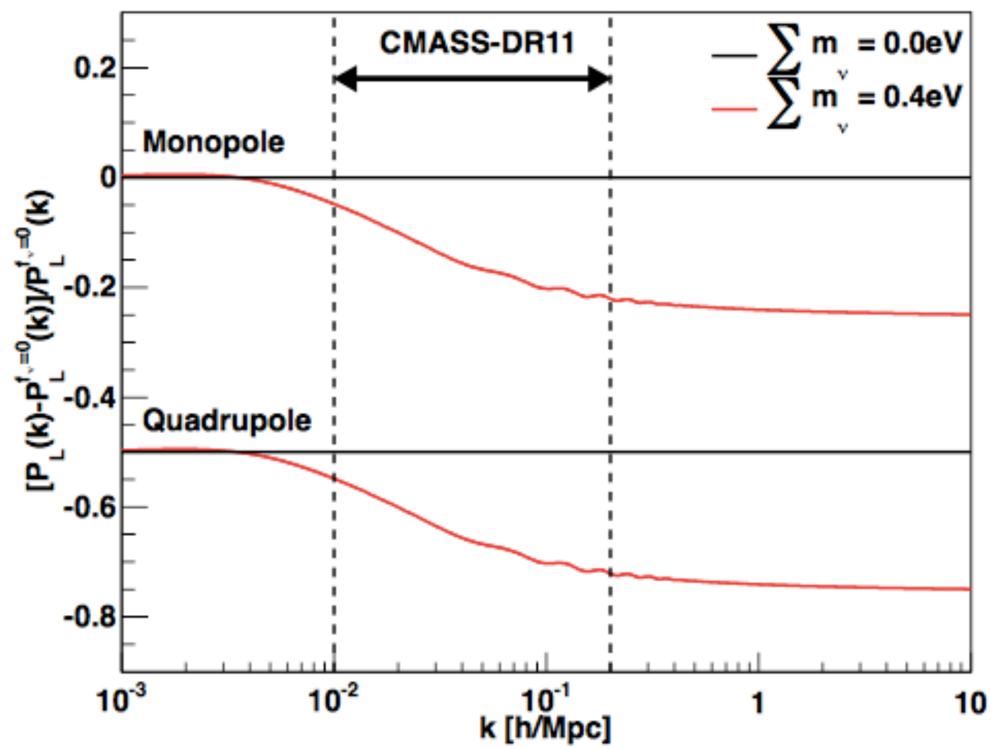


Figure 2. Relative amplitude difference between a linear power spectrum monopole (top) and quadrupole (bottom) with $\sum m_\nu = 0$ eV (black lines) and $\sum m_\nu = 0.4$ eV (red lines). We keep $\Omega_c h^2$ fixed when including the neutrino mass, so that the total physical matter density increases as $\Omega_m h^2 = \Omega_c h^2 + \Omega_b h^2 + \Omega_\nu h^2$. The black dashed lines show the fitting range for the CMASS-DR11 results of Beutler et al. (2013). We subtract 0.5 from the quadrupole for plotting purposes.

Beutler et al 2014

Observables: Spectroscopic Galaxy Clustering

sensitive to:

- change in amplitude of galaxy fluctuations at redshift(s) of measurement z
- change of rate of change of growth of matter fluctuations at z

degeneracies:

- dark energy/modified gravity
- astrophysics? galaxy bias?
- $\Omega_m h^2$ (total matter density)
- A_s (amplitude of primordial fluctuations)

systematics:

- modeling nonlinear P(k)
- modeling baryonic effects on P(k)
- modeling galaxy bias
- modeling redshift space distortions
- ?

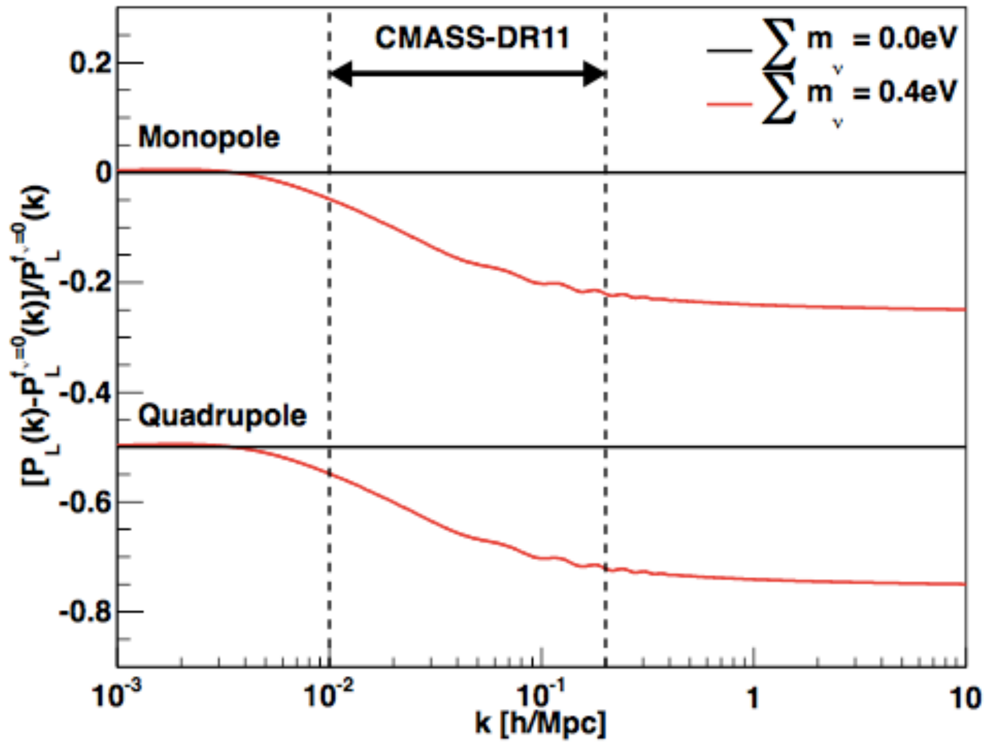


Figure 2. Relative amplitude difference between a linear power spectrum monopole (top) and quadrupole (bottom) with $\sum m_\nu = 0$ eV (black lines) and $\sum m_\nu = 0.4$ eV (red lines). We keep $\Omega_c h^2$ fixed when including the neutrino mass, so that the total physical matter density increases as $\Omega_m h^2 = \Omega_c h^2 + \Omega_b h^2 + \Omega_\nu h^2$. The black dashed lines show the fitting range for the CMASS-DR11 results of Beutler et al. (2013). We subtract 0.5 from the quadrupole for plotting purposes.

Beutler et al 2014

Observables: Spectroscopic Galaxy Clustering

sensitive to:

- change in amplitude of galaxy fluctuations at redshift(s) of measurement z
- change of rate of change of growth of matter fluctuations at z

degeneracies:

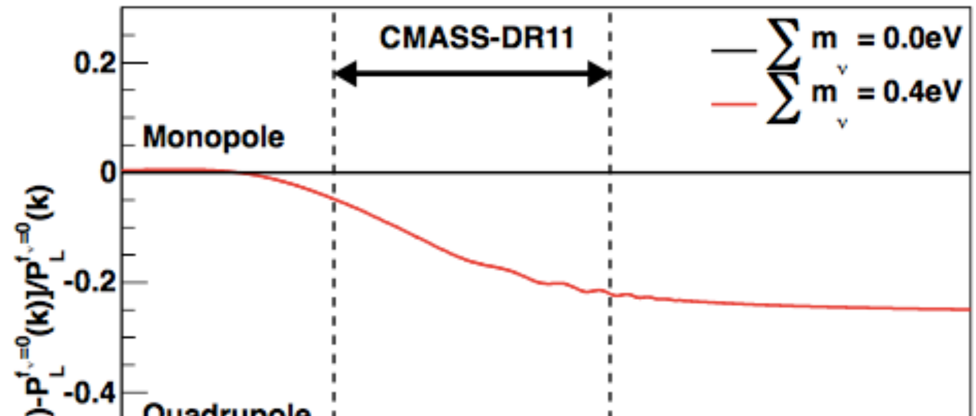
- Redshift surveys like DESI, with help from Planck and possibly lensing surveys, will measure the sum of neutrino masses to $\sim 0.01 - 0.02$ eV in the 2020's. This will give a strong detection of the minimum possible sum of masses ~ 0.06 eV, however, the mass hierarchy will only be distinguishable with luck, if the true sum of masses is right at the minimum.

Font-Ribera et al 2014

- A_s (amplitude of primordial fluctuations)

systematics:

- modeling nonlinear P(k)
- modeling baryonic effects on P(k)
- modeling galaxy bias
- modeling redshift space distortions
- ?



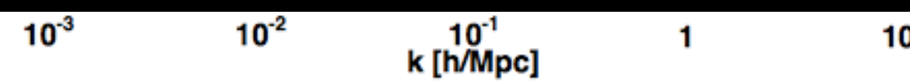


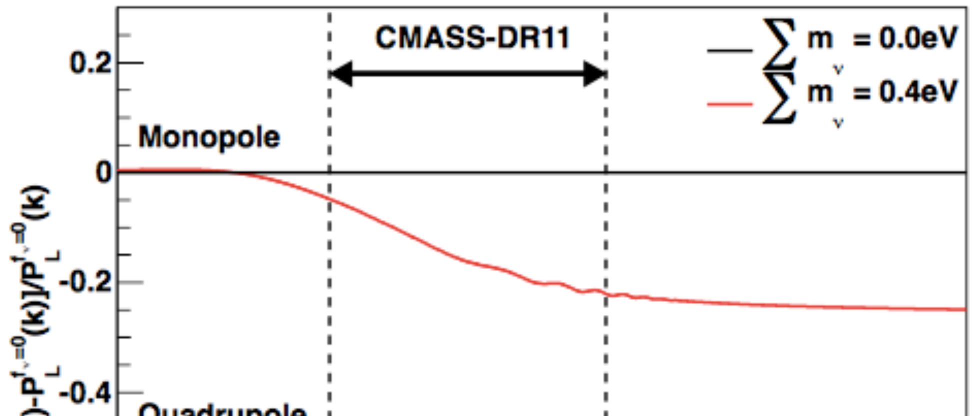
Figure 2. Relative amplitude difference between a linear power spectrum monopole (top) and quadrupole (bottom) with $\sum m_\nu = 0$ eV (black lines) and $\sum m_\nu = 0.4$ eV (red lines). We keep $\Omega_c h^2$ fixed when including the neutrino mass, so that the total physical matter density increases as $\Omega_m h^2 = \Omega_c h^2 + \Omega_b h^2 + \Omega_\nu h^2$. The black dashed lines show the fitting range for the CMASS-DR11 results of Beutler et al. (2013). We subtract 0.5 from the quadrupole for plotting purposes.

Beutler et al 2014

Observables: Spectroscopic Galaxy Clustering

sensitive to:

- change in amplitude of galaxy fluctuations at redshift(s) of measurement z
- change of rate of change of growth of matter fluctuations at z



degeneracies:

- Redshift surveys like DESI, with help from Planck and possibly lensing surveys, will measure the sum of neutrino masses to $\sim 0.01 - 0.02$ eV in the 2020's. This will give a strong detection of the minimum possible sum of masses ~ 0.06 eV, however, the mass hierarchy will only be distinguishable with luck, if the true sum of masses is right at the minimum.

Font-Ribera et al 2014

- A_s (amplitude of primordial fluctuations)

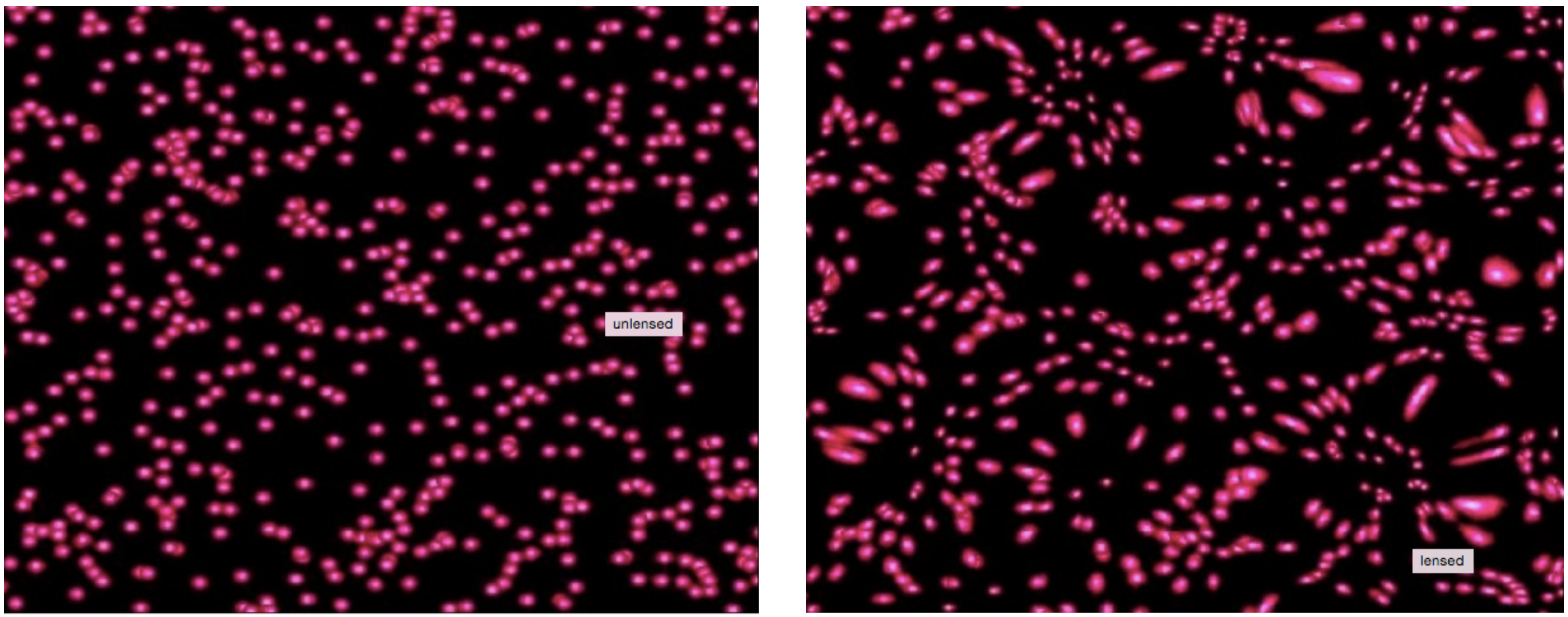
Figure 2. Relative amplitude difference between a linear power spectrum monopole (top) and quadrupole (bottom) with $\sum m_\nu = 0$ eV (black lines) and $\sum m_\nu = 0.4$ eV (red lines). We keep $\Omega_c h^2$ fixed when including the neutrino mass, so that the total physical matter density increases as $\Omega_m h^2 = \Omega_c h^2 + \Omega_b h^2 + \Omega_\nu h^2$. The black dashed lines show the fitting range for the CMASS-DR11 results of Beutler et al. (2013). We subtract 0.5 from the quadrupole for plotting purposes.

systematics:

- modeling nonlinear P(k)
- modeling baryonic effects on P(k)
- modeling galaxy bias
- modeling redshift space distortions
- ?

Beutler et al 2014

Observables: Photometric Galaxies, Weak Lensing Shear



(image from Smoot group)

Observables: Photometric Galaxies, Weak Lensing Shear

sensitive to:

- change in amplitude of galaxy fluctuations at redshift(s) of measurement z

degeneracies:

- $\Omega_m h^2$ (total matter density)
- A_s (amplitude of primordial fluctuations)
- dark energy/modified gravity
- astrophysics? (galaxy bias?)

systematics:

- modeling nonlinear P(k)
- modeling baryonic effects on P(k)
- intrinsic alignments
- ?

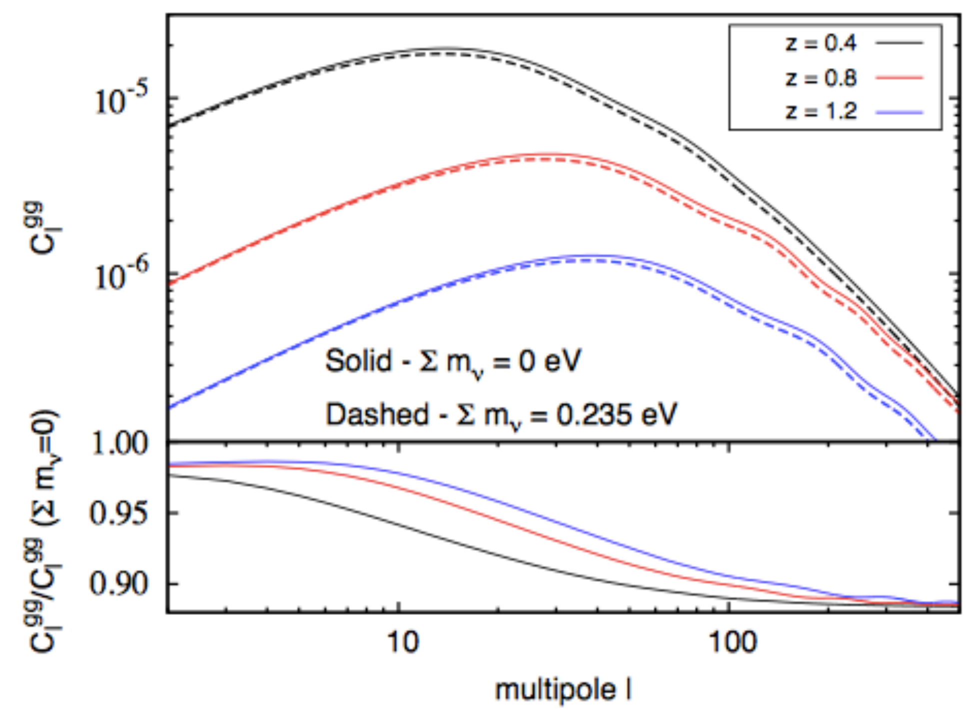


FIG. 3. Top panel: Angular clustering of galaxies in three redshift shells with mean photo-z of $z = 0.4$ (black), $z = 0.8$ (red) and $z = 1.2$ (blue). The solid lines depict models with massless neutrinos and dashed lines are for a ΛCDM model with massive neutrinos, where $\Omega_\nu = 0.005$ and $\sum m_\nu = 0.235$ eV. Bottom panel: The spectrum suppression relative to the case with massless neutrinos.

Zablocki 2014

Observables: Photometric Galaxies, Weak Lensing Shear

sensitive to:

- change in amplitude of galaxy fluctuations at redshift(s) of measurement z

degener

- $\Omega_m h^2$ (
- A_s (an

- dark energy/modified gravity
- astrophysics? (galaxy bias?)

systematics:

- modeling nonlinear P(k)
- modeling baryonic effects on P(k)
- intrinsic alignments
- ?

Planck + LSST, $\sigma_{M\nu} \approx 0.02$eV, + BAO 0.016eV

Font-Ribera et al 2013

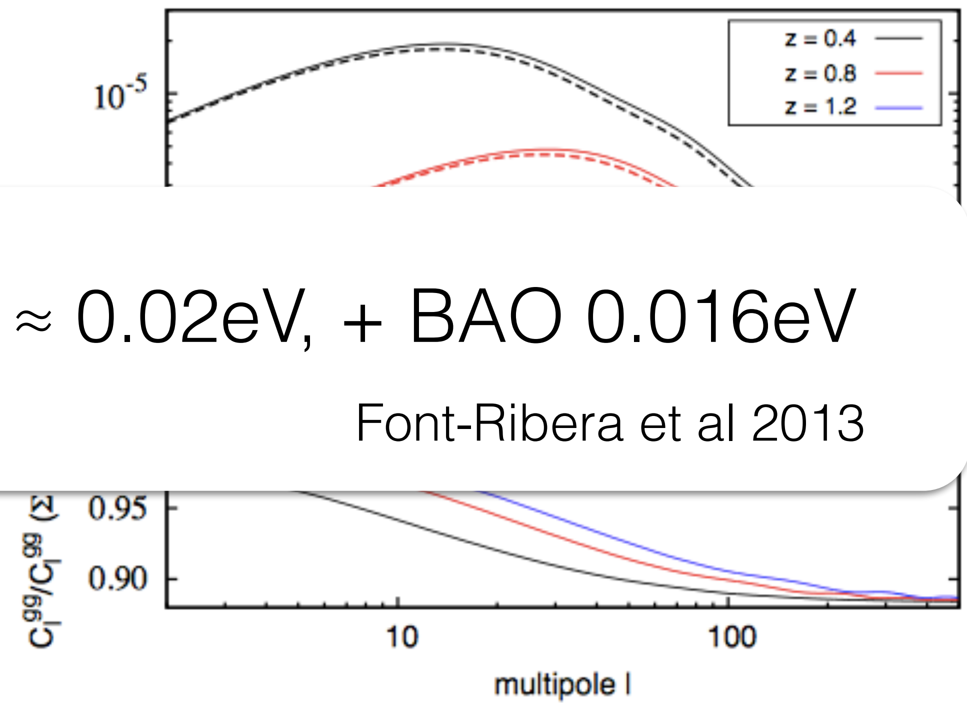


FIG. 3. Top panel: Angular clustering of galaxies in three redshift shells with mean photo-z of $z = 0.4$ (black), $z = 0.8$ (red) and $z = 1.2$ (blue). The solid lines depict models with massless neutrinos and dashed lines are for a ΛCDM model with massive neutrinos, where $\Omega_\nu = 0.005$ and $\sum m_\nu = 0.235$ eV. Bottom panel: The spectrum suppression relative to the case with massless neutrinos.

Zablocki 2014

Observables: Photometric Galaxies, Weak Lensing Shear

sensitive to:

- change in amplitude of galaxy fluctuations at redshift(s) of measurement z

degener

- $\Omega_m h^2$ (
- A_s (an
- dark energy/modified gravity
- astrophysics? (galaxy bias?)

systematics:

- modeling nonlinear P(k)
- modeling baryonic effects on P(k)
- intrinsic alignments
- ?

Planck + LSST, $\sigma_{M\nu} \approx$ 0.02eV, + BAO 0.016eV

Font-Ribera et al 2013

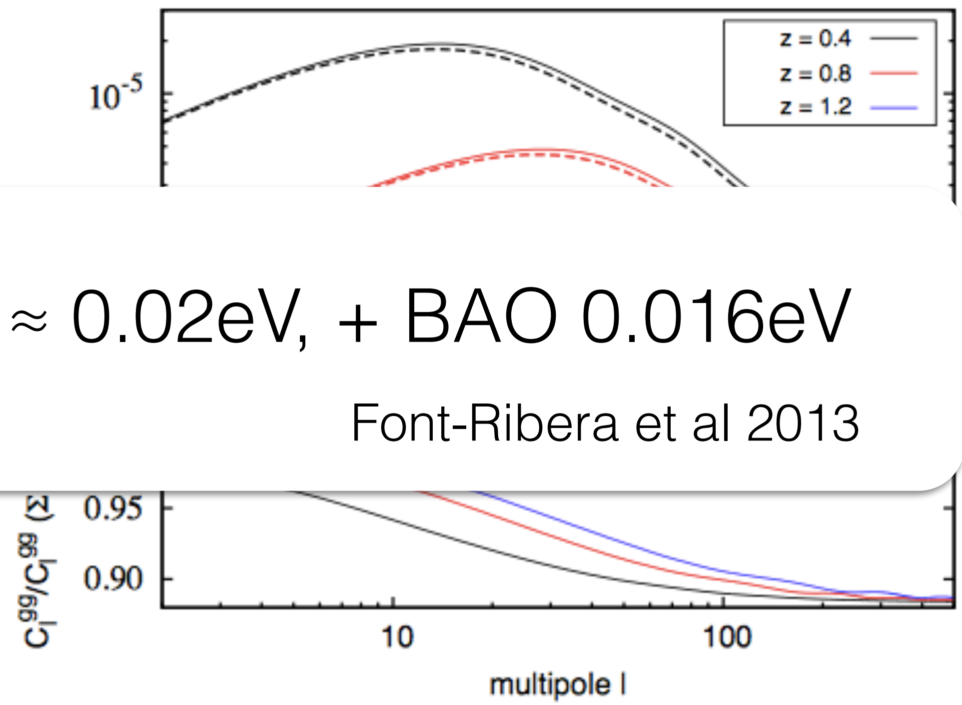


FIG. 3. Top panel: Angular clustering of galaxies in three redshift shells with mean photo-z of $z = 0.4$ (black), $z = 0.8$ (red) and $z = 1.2$ (blue). The solid lines depict models with massless neutrinos and dashed lines are for a ΛCDM model with massive neutrinos, where $\Omega_\nu = 0.005$ and $\sum m_\nu = 0.235$ eV. Bottom panel: The spectrum suppression relative to the case with massless neutrinos.

Zablocki 2014

Observables:

Cluster Abundance

sensitive to:

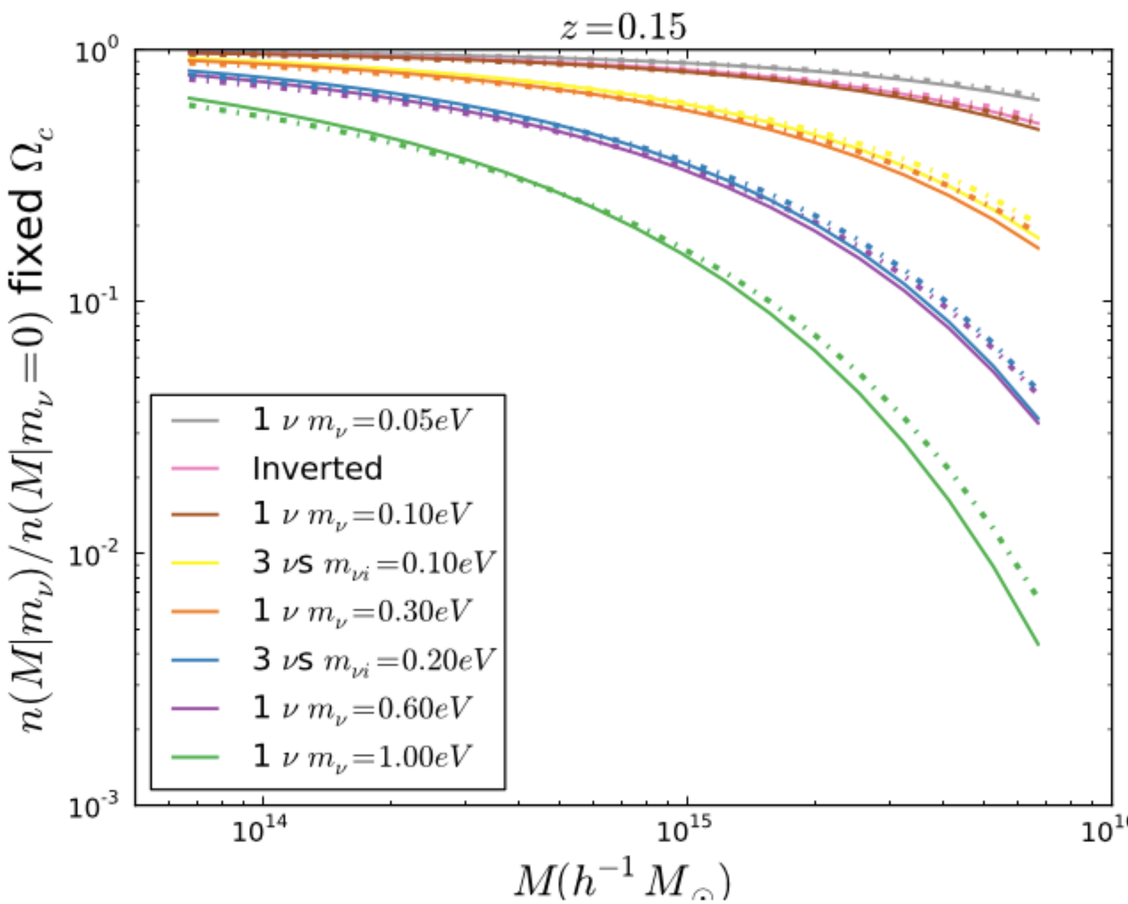
- change in amplitude of density fluctuations at redshift(s) of measurement z

degeneracies:

- $\Omega_m h^2$ (total matter density)
- A_s (amplitude of primordial fluctuations)
- dark energy/modified gravity

systematics:

- cluster mass measurements/ survey completeness
- modeling the cluster abundance
- ?



Loverde 2014

Other Observables:

- scale-dependent halo bias

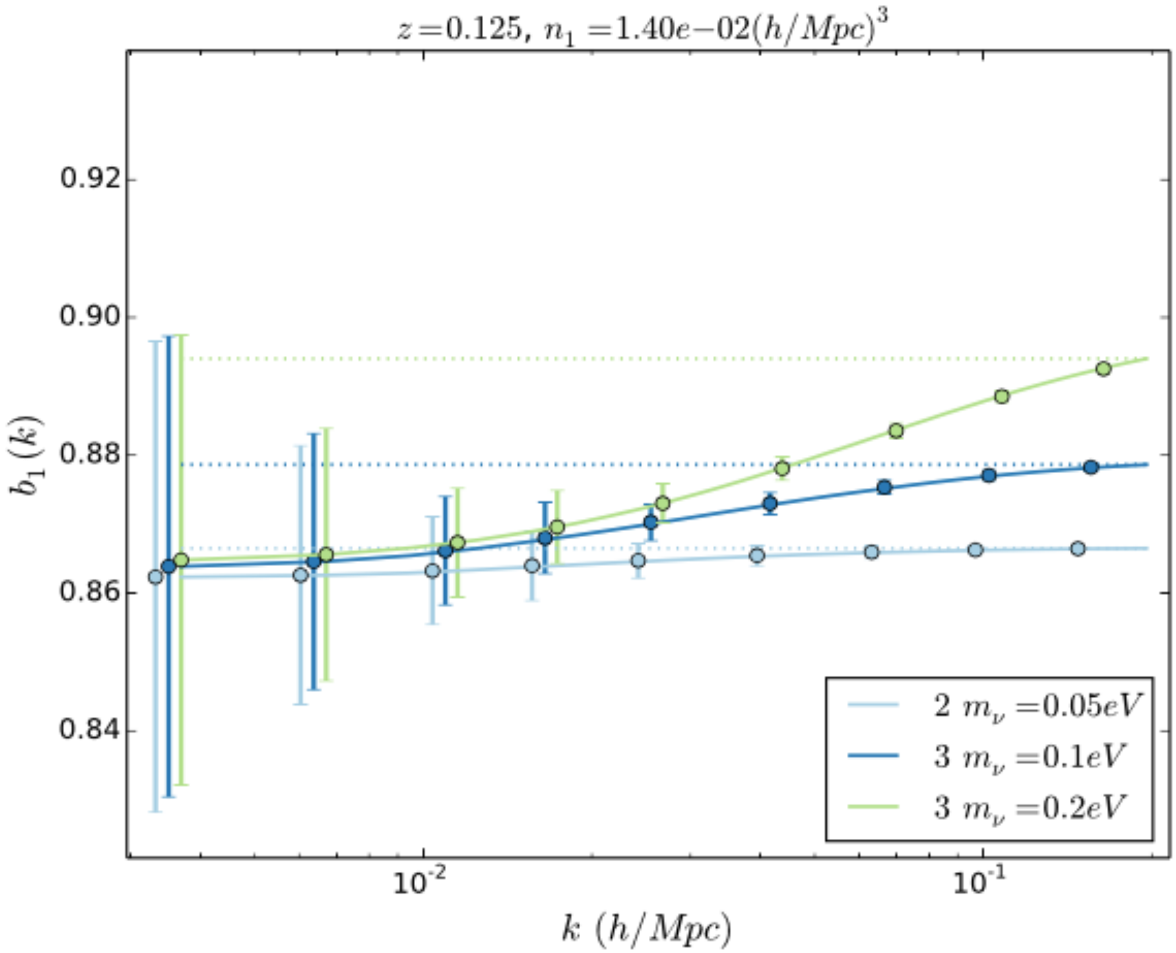
- CDM/neutrino relative velocities

- pairwise kSZ statistics

- . . .

Other Observables:

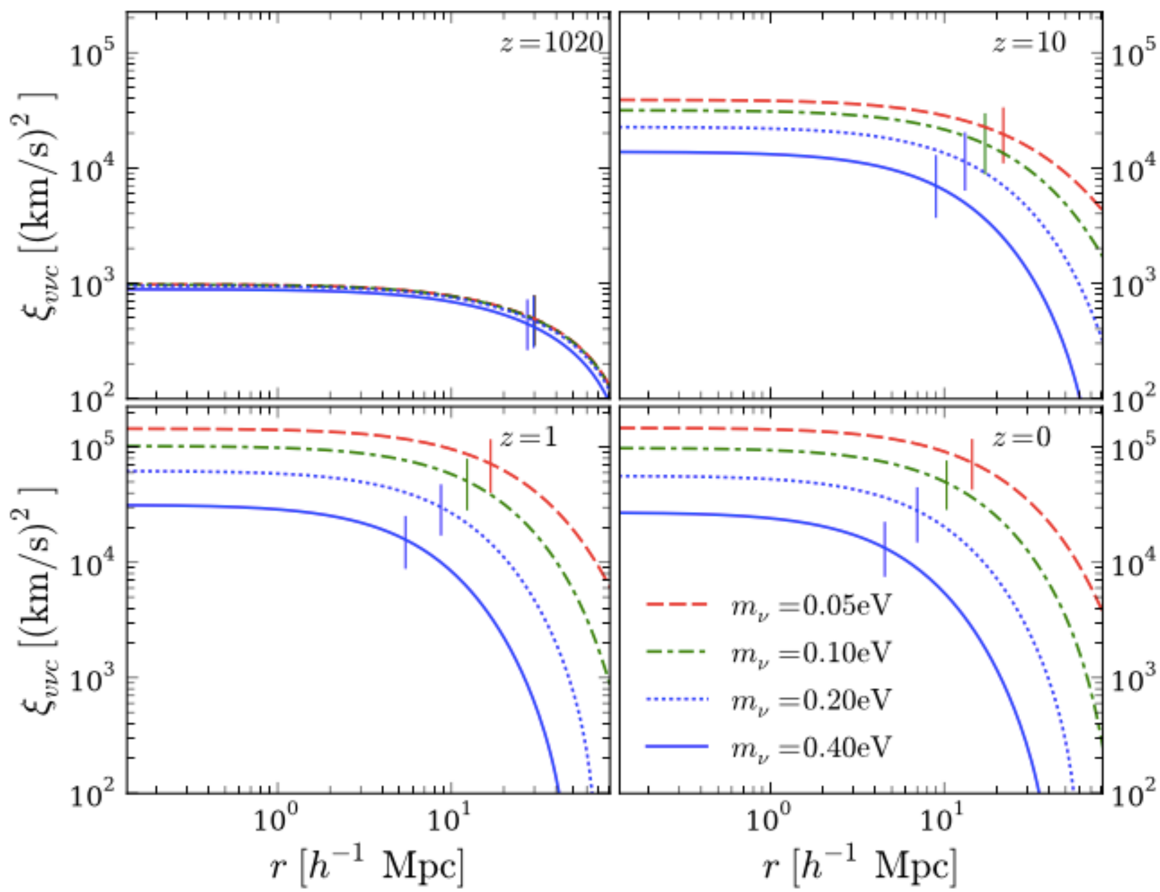
- scale-dependent halo bias



Loverde 2014

Other Observables:

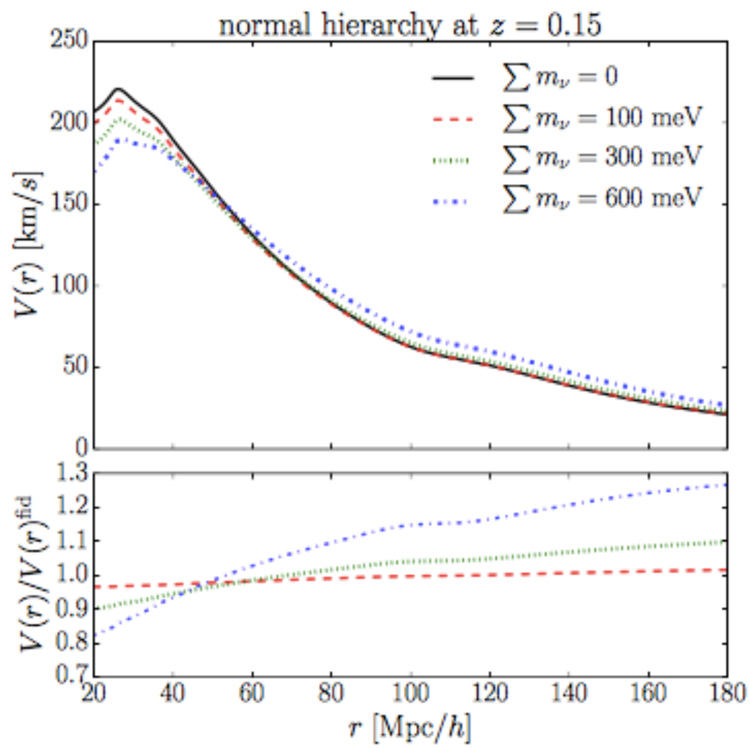
- CDM/neutrino relative velocities



Zhu, Pen, Chen, Inman, Yu 2014

Other Observables:

- pairwise kSZ statistics



Mueller, de Bernardis, Bean, Niemack 2014

Opportunity:

Detect neutrino mass scale!

Discover sterile neutrinos, an inconsistency with standard cosmological model, and/or neutrino oscillation data!

Opportunity:

Detect neutrino mass scale!

Discover sterile neutrinos, an inconsistency with standard cosmological model, and/or neutrino oscillation data!

Challenge:

Convince yourself that the detection is real

Opportunity:

Detect neutrino mass scale!

Discover sterile neutrinos, an inconsistency with standard cosmological model, and/or neutrino oscillation data!

Challenge:

Convince yourself that the detection is real

- compelling handle on astrophysical and observational systematics and possible degeneracies
- multiple probes
- multiple probes sensitive to different “neutrino-y” effects

Questions

How best to look for new physics (sterile neutrinos, an inconsistency with standard cosmological model, and/or neutrino oscillation data)?

How to convince yourself that the detection is real?

How to get more info than $\sum m_\nu$?